Experimental Investigation of the Influence of Obstacle in the Room on Passive Night-Time Cooling using Displacement Ventilation

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Experimental investigation of the influence of obstacle in the room on passive night-time cooling using displacement ventilation

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KEYWORDS: *Passive cooling, displacement ventilation, night-time ventilation; experiments; heat transfer; temperature efficiency.*

SUMMARY:
Night-time ventilation is a promising approach for reducing the energy needed for cooling buildings without reducing thermal comfort. The objective of this paper is to determine how an internal obstacle, such as a table, will influence the heat transfer in the room and the efficiency of night-time ventilation which uses displacement ventilation. Experimental work was conducted on the basis of the work in a similar previous study, performed by (Artmann 2010), and this is an extension of that work. Experimental results obtained for a case with a table were compared with the results obtained by Artmann et al. for a room with displacement ventilation, but without table.

The results obtained in the experiment with the table indicated that the mean heat flux was slightly lower but very similar compared to the case without the table. The heat flux at the ceiling was measured to be the same for both setups, whereas the heat flux at the floor was lower for the setup with the table. For the room with the table, especially for low air change rates, temperature efficiency is slightly reduced. Finally, experimental results indicate that there are no significant differences in heat discharged by the night time ventilation for the room with and without table.

1. Introduction

During the last decades a tendency in increased energy consumption in buildings for cooling has been observed in Europe and other highly developed countries. It is especially energy use for air-conditioning in office building and commercial building that contribute to increasing energy use for cooling. A promising approach to reduce energy use for cooling in office building is passive cooling by night-time ventilation. Passive cooling concepts by night time ventilation, is to cool a building with a large ventilation rate, when the external temperature is lower than the internal temperature. In Central and Northern Europe, this passive cooling strategy has the highest potential during the night time, when the outdoor air is usually below the indoor air temperatures at anytime of the year. Typically, the highest heat gains appear during the day, whereas the highest ventilation cooling potential is during the night. Therefore, it is essential for the building to have a high thermal capacity (Artmann 2007) (Lina Yang 2008). To make heat storage efficient, it is necessary to have a sufficient heat transfer at the building surface’s and high heat conduction of the internal construction elements is required.

The experimental study presented in (Artmann 2010), provides a detailed analysis of convection and radiation during night-time ventilation. This convective and radiative heat transfer depends on the air flow and the initial temperature difference between the inflowing air and the room surfaces. The results of these experiments demonstrated, how convection and radiation contribute to the total heat flow discharged from the room during night-time ventilation. It was observed that in the case with low convective heat transfer at the ceiling, large differences in surface temperature caused higher radiative heat flows from the ceiling to the floor. Thus it was discovered that it was beneficial to prevent warm air from accumulating below the ceiling. In the experiment with displacement ventilation conducted by (Artmann 2010), the location of the outlet opening was located very close to the ceiling. At low air flow rates, the temperature stratification and the high location of the outlet opening resulted in a very high temperature efficiency.

The objective of the experiment that is presented in this paper is to assess impact of an internal obstacle, such as a table, on convection and radiation during the night time ventilation in the case when the displacement ventilation principle is used. An obstacle arises when a table is placed in one of the corners of the test chamber. The temperature distribution and near-surface velocities changes due to the fact that the air flow pattern in the room has been changed. As a consequence, the additional furnishing (a table) might cause a change in radiative and convective heat exchange between indoor room surfaces. Finally, the results obtained in a full scale experiment are compared with the experimental results by (Artmann 2010), who conducted experiments for the empty chamber. The comparison presented in this paper can be done only because the test chamber used by (Artmann 2010) is the same as the one used in experiment in here presented paper.

2. Test room setup

The test room used for the experiment is located at Aalborg University. The plan of the test facility is presented in Fig. 1.The thermal properties of the material used on the internal surfaces of the room were measured or taken from the literature (Artmann 2008). The values used for calculations, including estimated uncertainties are summarised in Table 1.

In the test room it is the ceiling that contributes the most to the thermal mass of the room construction. To increase thermal mass of the ceiling an additional 5 layers of plasterboard were attached.

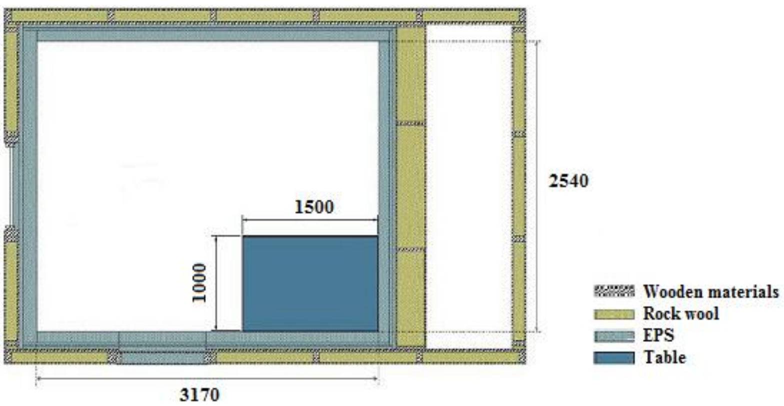

FIG 1. Plan view of the test room with table in the corner.

In Fig. 1 can be noticed that there is an empty chamber on one side of the test room. This chamber is present only due to previous experiments that were conducted at this facility and during here presented experiments the temperature in the chamber is kept the same as in the laboratory.

TABLE 1. Material properties

Materials	λ [W/mK]	ρ[kg/m3]	Cp [J/kgK]	ε [-]
Gypsum board	0,28±0,001	1127±104	1006±100	-
Expanded polystyrene (EPS)	0,37±0,001	16,0±0,1	1450±100	0,73±5%
White paint (ceiling)	-	-	-	0,90±5%
Rockwool	0,036	25	800	-
Plywood	0,11	411	1800	-

Schematic configuration of the ventilation inlet and outlet for displacement ventilation is presented in the Fig. 2.

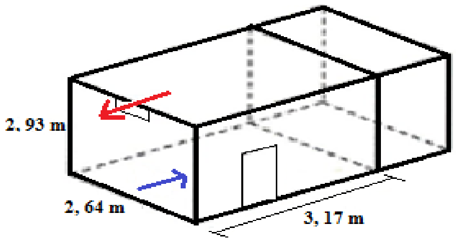

FIG 2. Configuration of the air in- and outlet openings of the test room for displacement ventilation.

For displacement ventilation, a semicircular displacement inlet device was located in the floor of the test room, see Fig. 3

FIG 3. Inlet device for displacement ventilation.

A mechanical ventilation system was installed in order to provide air at the defined temperature to the test chamber. The ventilation was designed to be able to provide air flow of about 56 – 330 m^3/h, which corresponds to 2,3 – 14 air change rate per hour (ACR). Air flow rate was measured using an orifice installed in the supply duct. The pressure difference on the orifice was measured by means of a micro-manometer.

2.1 Measuring instrumentation

Temperature measurements from the chamber were logged by three Fluke Helios Plus data loggers and one Grant Squirrel data logger. All thermocouples used in the experiment are K type thermocouples with sensitivity of 0,41 μV/K.

The ceiling of the chamber was divided into 22 sections, where five thermocouples were located in the different layers, see Fig. 4 and 5 respectively, of the gypsum ceiling. Additionally, a series of thermocouples was also attached 30 cm under the surface of the ceiling in order to measure local temperature of the air, Fig 5.

It was desirable not only to measure the temperature at the ceiling, but also at the walls, at the table and at the floor. These surfaces were also divided into smaller sections. All the surfaces of the walls and floor were divided into three minor surface areas, and thermocouples were attached the same way as on the ceiling, see Fig. 6. Due to presence of the table, 6 more thermocouples were located as presented in Fig. 7.

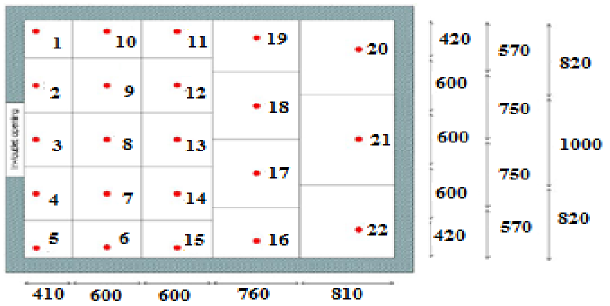

FIG 4.Ceiling divided into 22 sections.

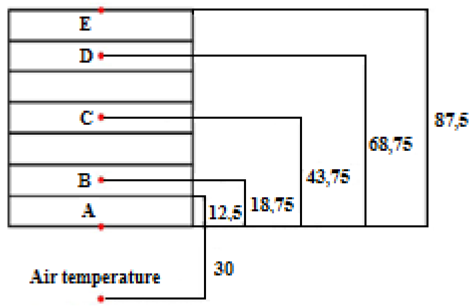

FIG 5.Attachement of the thermocouples in the ceiling- section view.

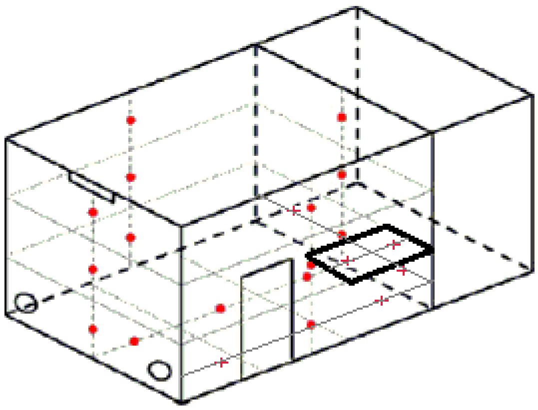

FIG 5.Location of the thermocouples in the test chamber. Crosses represent new additional thermocouples.

Inlet and outlet temperature were measured to determine the heat flow that was removed from the test chamber by the ventilation. In the case of the displacement ventilation, a thermocouple was located in the location where the duct entered the room and in the inlet device. The outlet temperature was measured in the centre of the outlet opening.

2.2 Procedure for experiments

In total 7 experiments were conducted for displacement ventilation and chamber with table. Parameters that varied; was ACR and respectively initial temperature difference (ΔT_0), see table 2.

Initially the test room had a homogeneous temperature of the inlet temperature, which was equal to the lab temperature. Then, half an hour after closing the test room door, the Helios data logger was switched on manually. The data logger was then recording data from the test room for the next 12 hours. As it took some time until the temperature measured at the inlet was constant, the initial temperature difference, ΔT_o was defined as the difference between the mean temperature of the ceiling element before the experiment and the mean inlet air temperature measured during the last 10 hours of the experiment.

TABLE 2. List of experiments

Experiment no.	ACR	ΔT_o
1	4,2	0,5
2	4,3	3,1
3	6,6	1,7
4	6,6	5,1
5	13,2	4,2
6	13,2	6,0
7	14,0	0,3

2.3 Data evaluation

The experiment results presented in (Armann, 2010) are used in this study as the base of reference and for comparison to the results presented in this article. The study presented in this article applies the same concept for data evaluation as presented in (Artmann 2008).

3. Results

In the Fig. 6, is presented mean convective heat flux $q_{conv,\ tot}$, from all room surfaces, which depends on the difference between the mean surface temperature, $\overline{T}_{surface}$ and the inlet air temperature, T_{inlet}. During each experiment the temperature difference decreases over the time and as a consequence, heat flux also decreases. For both, experiment with and without the table relation is very close to linear. As well for experiment with and without the table, gradient of the lines can be interpreted as average heat transfer coefficients that can be calculated according to the Eq. (1).

$$h' = \frac{\dot{q}_{conv,tot}}{\overline{T} - T_{inlet}} \tag{1}$$

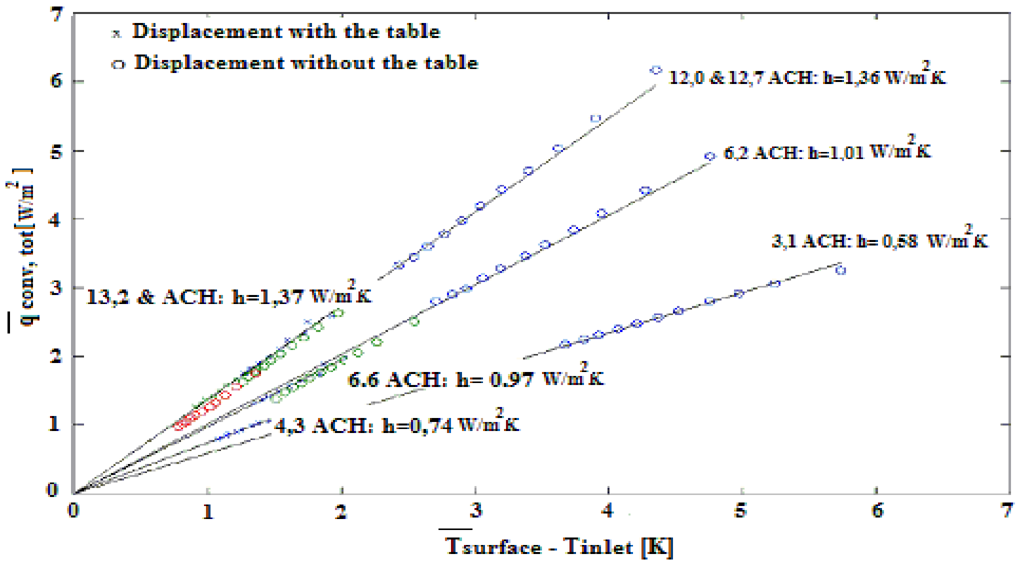

FIG 6. Mean heat flux in the test chamber in a function of temperature.

Since, average heat transfer presented in Fig. 6 is a mean value it can not stand for what happens locally, for instance, at the ceiling. Therefore, heat flux at the ceiling is presented separately in Fig. 7.

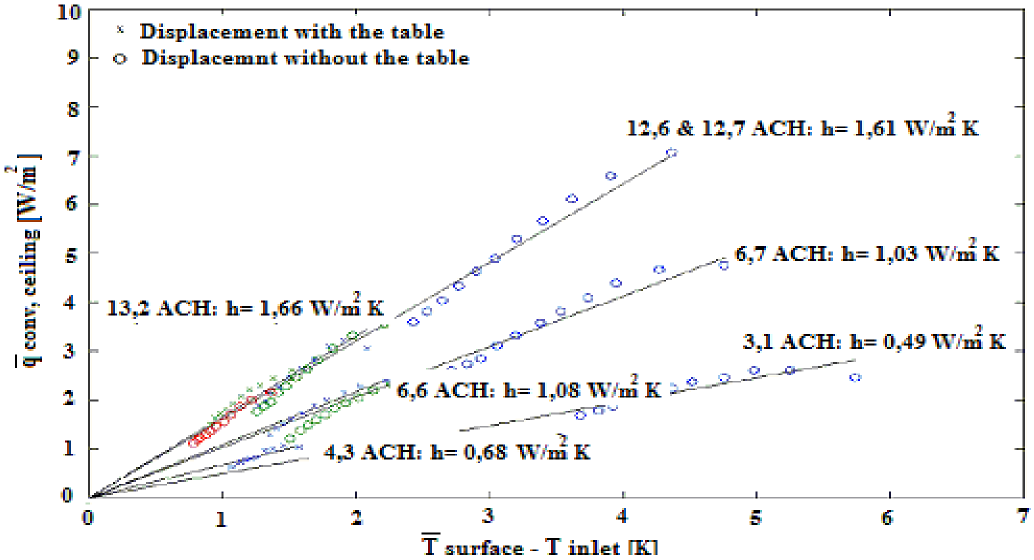

FIG 7. Mean heat flux at the ceiling.

3.1 Ratio of convective to total heat flow

In order to present effect of the air jet on the heat transfer at the ceiling, the ratio of the convective heat flow to the total flow from the ceiling is defined as in the Eq. (2).

$$\gamma = \frac{Q_{conv,ceiling}}{Q_{cond,ceiling}} \tag{2}$$

Where $Q_{conv,\, ceiling}$ heat flow by convection at the ceiling (W)
$Q_{\text{cond, ceiling}}$ heat flow by conduction at the ceiling (W)
γ convection ratio (-)

The air flow pattern is characterised by the dimensionless Archimedes number. To avoid an arbitrary definition of characteristic length scale, only the temperature difference and air flow rate was used, see Eq. 3.

$$Ar = \frac{\overline{T}_{surface} - T_{inlet}}{V^2} \tag{3}$$

Where $\overline{T}_{\text{surface}}$ Mean surface temperature (°C)
$\overline{T}_{\text{inlet}}$ Inlet air temperature (°C)
V^2 air flow (m^3/s)

By letting γ depends on the Archimedes number which characterize the flow pattern, Fig. 8 can be displayed for both set ups, with and without the table.

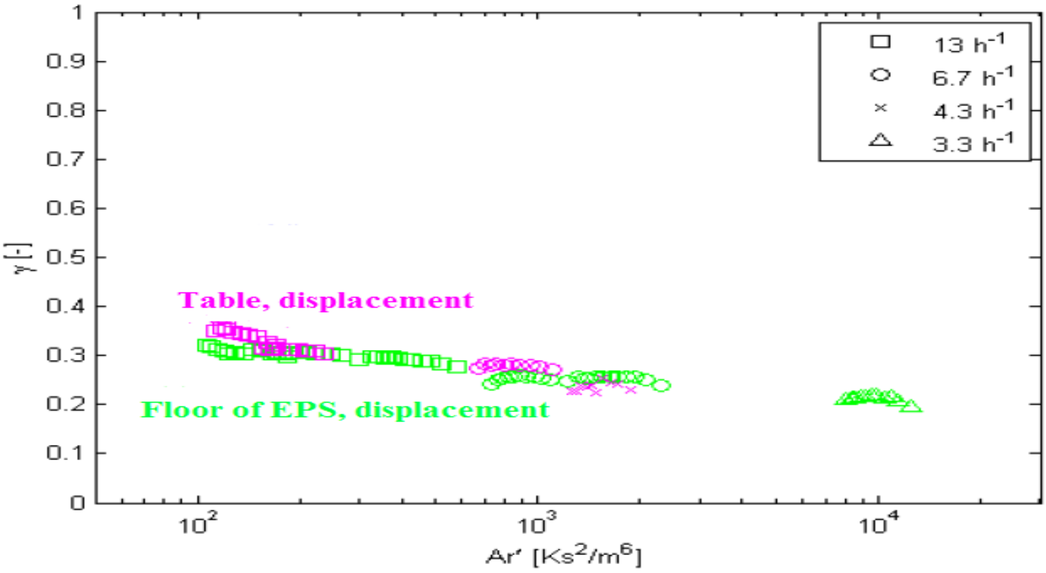

FIG 8. γ depending on Ar for displacement ventilation.

3.2 Performance of night time ventilation

The performance of night time ventilation is given by Eq. 4.

$$\eta = \frac{T_{outlet} - T_{inlet}}{\overline{T}_{surface} - T_{inlet}} \qquad (4)$$

Where T_{outlet} Outlet air temperature (^{o}C)
η Temperature efficiency (-)

The temperature efficiencies of displacement ventilation, obtained for an empty room and for the room with the table, are presented in Fig. 9.

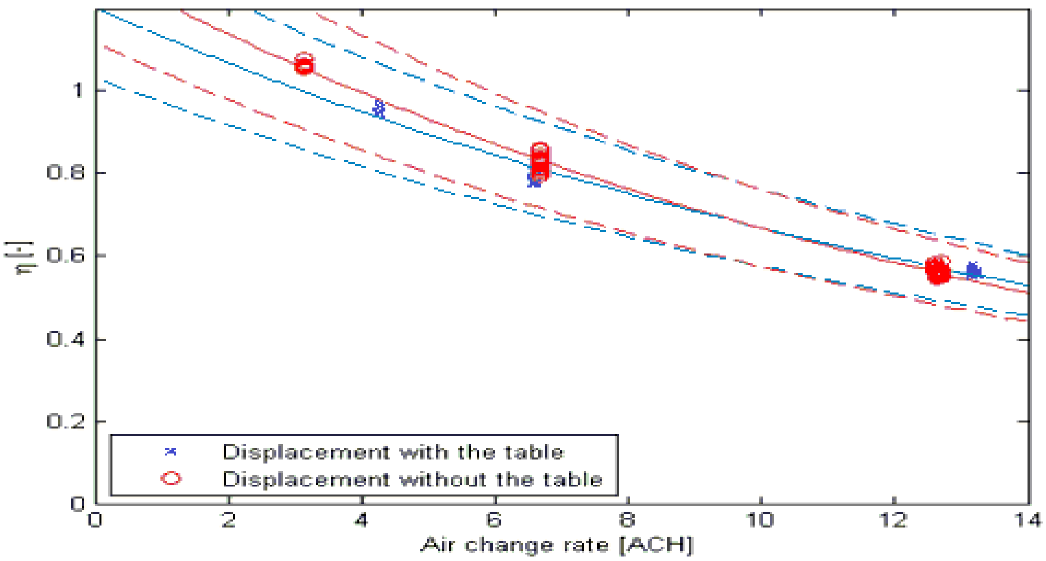

FIG 9. Temperature efficiency, η depending on the ACR for displacement ventilation, hourly values, results for set up with and without the table.

4. Discussion

The purpose of this study was to measure the final difference and distribution between the heat transfer by convection and radiation in the night time-ventilated room that was furnished with and without the table. Therefore, this paper will compare the results of these two setups. For more specific information the reference is given to (Artmann 2010).

In Fig. 6, it can be observed that the presence of the table does not significantly influence average convective heat transfer coefficient in the test chamber. The calculated deviation for the two setups is approximately 3,96 % when using ACR= 6,6 with the table and ACR = 6,7 without the table.

In the Fig. 7, for ACR= 6,6 with the table and ACR = 6,7 without the table can be observed that the mean heat flux at the ceiling differs for these two cases of 9,84%. This deviation indicates that the heat flux at the ceiling contributes significantly to the overall heat transfer in the test chamber.

The convective ratio that was presented in Fig. 8, does not differ in the room with and without the table.

Moreover, it can be noticed that the temperature efficiency for the room with the table is lower than for the room without the table for low ACR. The opposite situation can be noticed for high ACR, (see Fig. 9). It is remarkable that for displacement ventilation the temperature efficiency exceeds 1. This phenomenon occurs because of temperature stratification in the room. However, it can be observed in Fig. 9 that the temperature efficiency for displacement ventilation drops remarkably with increased ACR and that for ACR higher than 10,5 h^{-1}, it is mixing ventilation that had higher efficiency, see (Artmann 2010).

5. Conclusion

The experimental results indicated that the internal obstacle, such as a table, does not have a significant influence on the overall heat transfer in the room when using displacement night time ventilation. Heat transfer due to convection and radiation preserve almost the same ratio distribution as for the case without the table. On the other hand, the temperature efficiency differs for the setup with the table and without the table, but significant differences can be observed only for low ACR.

Finally, it can be concluded that relatively small internal furnishing elements with regards to flooring area should not have decisive influence on performance of night-time cooling by displacement ventilation.

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